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Outlook of carbon capture technology and challenges

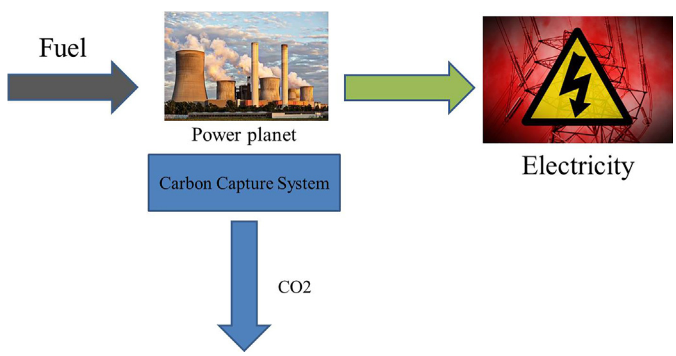
Tabbi Wilberforce [a], Ahmad Baroutaji [b,*], Bassel Soudan [e], Abdul Hai Al-Alami [c], Abdul Ghani Olabi [c,d]

[a] Institute of Engineering and Energy Technologies, University of the West of Scotland, UK
[b] School of Engineering, Faculty of Science and Engineering, University of Wolverhampton, UK
[c] Dept. of Sustainable and Renewable Energy Engineering, University of Sharjah, P.O. Box 27272, Sharjah, United Arab Emirates
[d] School of Engineering and Applied Science, Aston University, Aston Triangle, Birmingham B4 7ET, UK
[e] Department of Electrical and Computer Engineering, University of Sharjah, P.O. Box 27272, Sharjah, UAE

HIGHLIGHTS

- The main carbon capture technologies are reviewed.
- Comparison between the types of carbon capture technology is presented.
- Challenges of using these technologies in the capture of carbon dioxide is discussed.
- Future prospects of some of these technologies is presented.

GRAPHICAL ABSTRACT



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ABSTRACT

The greenhouse gases emissions produced by industry and power plants are the cause of climate change. An effective approach for limiting the impact of such emissions is adopting modern Carbon Capture and Storage (CCS) technology that can capture more than 90% of carbon dioxide (CO_2) generated from power plants.
This paper presents an evaluation of state-of-the-art technologies used in the capturing CO_2. The main capturing strategies including post-combustion, pre-combustion, and oxy – combustion are reviewed and compared. Various challenges associated with storing and transporting the CO_2 from one location to the other are also presented. Furthermore, recent advancements of CCS technology are discussed to highlight the latest progress made by the research community in developing affordable carbon capture and storage systems. Finally, the future prospects and sustainability aspects of CCS technology as well as policies developed by different countries concerning such technology are presented.

1. Introduction

Global warming is a major issue for most research centers and governmental institutions around the world (Wilberforce et al., 2017a; Wilberforce et al., 2017b; Wilberforce et al., 2015; Wilberforce et al., 2017c; Wilberforce et al., 2017f). It occurs due to high amounts of CO_2 in the airspace. Currently, most countries around the world still rely heavily on fossil commodities, which release significant amounts of CO_2, for power generation where almost 85% of power generated across the globe is from fossil fuel (Wilberforce et al., 2017d; Wilberforce et al., 2017e; Wilberforce et al., 2016; Ijaodola et al., 2018). A drastic

* Corresponding author.
E-mail address: ahmad.baroutaji2@mail.dcu.ie (A. Baroutaji).

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substitution of the traditional power plant with alternative clean energy generation mediums, which produce no CO_2, is virtually impossible in the near future. Therefore CCS technology has received increased awareness by research community. CCS technology helps in reducing carbon dioxide in the atmosphere that lead to depletion of the ozone layer and climate change (la Sota et al., 2017). It is expected that the next few years will see CCS as one of the cheapest methods for minimizing greenhouse gases (Nogalska et al., 2018; Kim et al., 2017). Main steps for implementing CCS in any power plant are presented in Fig. 1.

The CCS process starts with capturing the carbon dioxide generated by the biomass or fossil commodities. The carbon dioxide then undergoes a compression process to form a dense fluid. This helps in transporting the CO_2 as well as storing it. Dense fluid is transported via pipelines and then injected in an underground storage facility.

The current CCS technologies are generally very expensive and significant developments are needed to develop a more affordable CCS technology. Thus, the main objective for this investigation is to review CCS technologies and to explore the recent efforts made by the scientific community to come out with a new approach that can reduce the overall cost of this vital technology (Su et al., 2009).

2. CO_2 capturing technologies

Significant amounts of CO_2 are produced during the combustion of natural gas. This amount of CO_2 is either directed towards the atmosphere or used in manufacturing plants to produce other commodities as in food processing industry (Streets et al., 2018). However, small quantity of the generated carbon dioxide is reused by manufacturing industry as well as most of the carbon dioxide eventually ends up in the atmosphere (Alonso-Moreno and García-Yuste, 2016).

Several strategies for capturing carbon dioxide from gaseous mixtures have been designed and utilized in the industry. Fig. 2 depicts the recent technologies used for capturing carbon dioxide. The type of technology is determined by the purity and state of the gas in relation ambient conditions surrounding the CO_2 (López et al., 2018). Carbon dioxide capturing systems help in elimination of pollutants from the carbon dioxide during natural gas refining process as well as the generation of H, NH_3 and other chemicals for industrial purposes.

Overall aim for all carbon capture and storage technologies is to generate carbon dioxide that can be stored in a geological formation. To materialize this, carbon dioxide must be compressed to a liquid state in order to be transported easily through pipelines and eventually pumped into a geological formation. The carbon compression stage can thus be defined as part of the CCS system (Coutris et al., 2015; Benbi, 2018). Today, the technologies utilized for CCS are grouped as pre – combustion or post – combustion systems. These technologies are named depending on the timing when the carbon is eliminated that is prior or after the fossil fuel combustion (López et al., 2018). There is another CCS technology, known as the oxyfuel or oxy – combustion, which is still under developmental stages and it requires sometime before it becomes commercially acceptable. The technology used by power plants is similar to that used by some industrial activities devoid of burning.

2.1. CO_2 separation techniques for CCS

2.1.1. Physical absorption

There are two main stages with the physical absorption process. These are the absorption and stripping process. The absorption process involves treated gas being in contact with solvent stream and the CO_2 being captured by the solvent physically. The stripping involves CO_2 and solvent which is normally saturated is introduced to heat to produce new solvent and releasing the CO_2 at the apex of the stripping Chamber. Extent of CO_2 absorption for solvent is built around Henry's law. Dissolution of CO_2 in the liquefied solvent is due to electrostatic forces. Low temperature as well as high pressure are the best operating conditions for Physical absorption. Other conditions like high temperature but low pressure affects physical desorption. Physical absorption has good absorption characteristics compared to chemical absorbent (Romano et al., 2010; Martın et al., 2011). Its regeneration can be achieved via depressurization operation at lpw energy demand. This is the main reason for their dominance in pre-combustion carbon capture technology. They are useful in IGCC power plants elimination of carbon dioxide from synthesis gas, natural gas treatment as well as acid gas recovery as well. It must be noted that the capacity for absorption absorbent is useful at lower temperatures physically. It implies that reducing the temperatures of treated gas streams before absorption is very important (Schell et al., 2012). The well-known physical absorption process involves Selexol, Rectisol, Purisol and Fluor method.

2.1.2. Adsorption

Adsorption is slightly different from absorption because adsorption includes specific creation of physical and chemical connection between CO_2 and surface of the adsorbent. The adsorbed CO_2 then disappear via pressure swing adsorption (PSA) or temperature swing adsorption (TSA) in order to regenerate the adsorbent material. The adsorbent which is saturated is heated in Temperature swing adsorption to operating conditions at which physical and chemical bond is disintegrated leading to the detachment of adsorbed reactants but for pressure

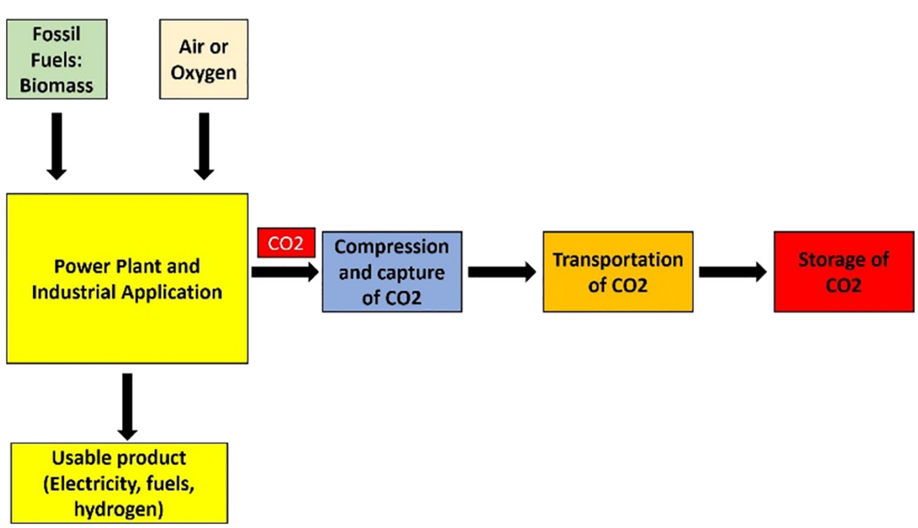


Fig. 1. Steps for carbon capture in a power plant and industrial application (Su et al., 2009).

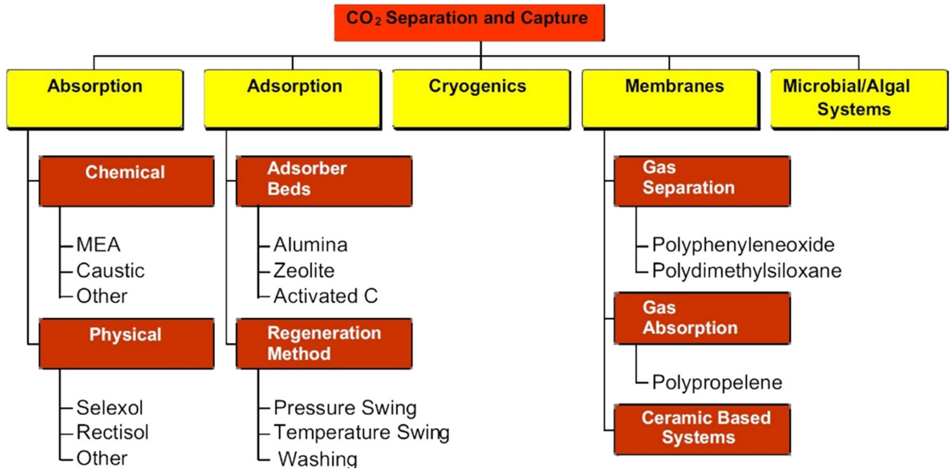


Fig. 2. Various technologies used in CCS (Su et al., 2009).

swing adsorption there is reduction of pressure to generate the same effect. When the CO_2 concentration is insignificant, temperature swing adsorption is often used but when the CO_2 concentration is high PSA is preferred (Casas et al., 2013; Jiang et al., 2015). Pressure swing adsorption is useful because of its short temporal need for regenerating the adsorbent. Some well-known physical adsorbent are zeolite and amine sorbents.

2.1.3. Membrane technology

Knudsen diffusion principle is the phenomenon that leads to membrane separation. CO_2 dissolves in the membrane and diffuse via rate proportional to its partial pressure gradient. Utilization of non-facilitated membrane technology is predominant in CO_2 elimination from natural gas and where the carbon dioxide partial pressure is high. In capturing carbon from flue gas because the carbon dioxide is less, there would be more energy imposed because compression work is need to support enough driving force to obtain the required carbon capture ratio. Enhancement of its selectivity is dependent on how permeable the membrane is designed to be. It implies that even though it has many merits like low environmental effect and degradation, integrating it to power plant already in existence poses a challenge. Researchers today are investigating on many ways of averting this challenge. The facilitated transport membrane separation is one of the newly designed approach recommended by researchers around the world. It is made up of mobile or liquid phase carrier that support movement of CO_2 as bicarbonate. This will support the permeability as well as the selectivity of CO_2 across the membrane. The mixed matrix membrane is also new type of membrane technology (Kang et al., 2015; Park et al., 2015a; Dai and Deng, 2016). They are made up of polymer membranes fillers. Some of the fillers are; zeolite, mesoporous silica and zeolitic imidazolate. These modified membranes reduce the processing cost and increase permeability. The strength and stability with respect to heat for these membranes are very good. Other new type of membrane separation technology is the gas membrane contactor. These types of membranes are not dependent on the Knudsen diffusion approach. The membranes for the gas membrane contactor only act as a point of application between the flu gas as well as CO_2 absorption solvent. They show compactness of the membrane system and high selectivity of amine-based absorption process. Their main demerits are that there are limitations in terms of mass transport because of resistance on the membrane framework.

2.1.4. Cryogenic separation

This approach involves several compression applications at ambient temperature as well as pressure for separating the gas. This technique is suitable for producing liquid carbon dioxide (Dai and Deng, 2016). It is ideal for carbon dioxide capture in high concentrations. This technology can also be used in place of amine-based scrubbing method because it utilizes water in lesser quantity, uses cheap chemical agents, corrosion resistant and less effect on the environment in terms of pollution. This concept also supports ambient pressure operation as well as liquid CO_2. They therefore support CO_2 transmission economically. Cryogenic separation has some limitations too (Zheng et al., 2016). It is energy intensive due to the operating temperature range being low hence high cost of operation. Formation of ice in cryogenic approach often causes the piping system being blocked and this reduces the drop-in pressure causing safety issues. It therefore becomes important that the amount of moisture is removed before the separation process. This process adds to the initial cost of using this technology.

2.2. Pre – combustion approach

This technology employs the separation of carbon dioxide from fossil commodities prior to burning process being started (Lueking and Cole, 2017). This technology can further be explained as a reacting fuel and O_2 gas to generate carbon monoxide, hydrogen as well as fuel gas. A pure hydrogen fuel stream is obtained after the removal of carbon dioxide (Alonso et al., 2017). By means of integrated gasification, carbon dioxide can be obtained. The technology is also applicable to power plants that uses natural gas (Zhang et al., 2019; Smith et al., 2012). Fig. 3 shows a diagram of carbon dioxide capture using the pre combustion technology approach. Table 1 also capture recent studies conducted in this field.

The first major step conducted during the elimination of carbon from fuel is to change the fuel to a form that is quite easy to capture. A reaction between coal with steam and oxygen gas is the usual phenomenon for power plants fueled by coal and the reaction occurs at higher temperature as well as pressure (Zhang et al., 2019). End product of this reaction is a fuel made up of CO as well as mixture of hydrogen called syngas. This gas can further go through a combustion process to produce power in power plant. The power generated is often referred to as Integrated Gasification Combined Cycle (IGCC) power. In second step of this process, the carbon monoxide obtained in first step is transformed into carbon dioxide via a reaction with steam. This leads to the formation of carbon dioxide and hydrogen.

A glycol solvent, known as Selexol, is used to trap the carbon dioxide through a chemical process. This results in purified hydrogen gas which goes through another plant to produce power shown in Fig. 3(a). Easy and cheaper separation of carbon dioxide due to the operating pressure being high as well as excellent concentrations of carbon dioxide using IGCC plants makes them the mostly preferred option by the research community even though they are very expensive compared to the traditional coal combustion plants. The operational approach for pre-

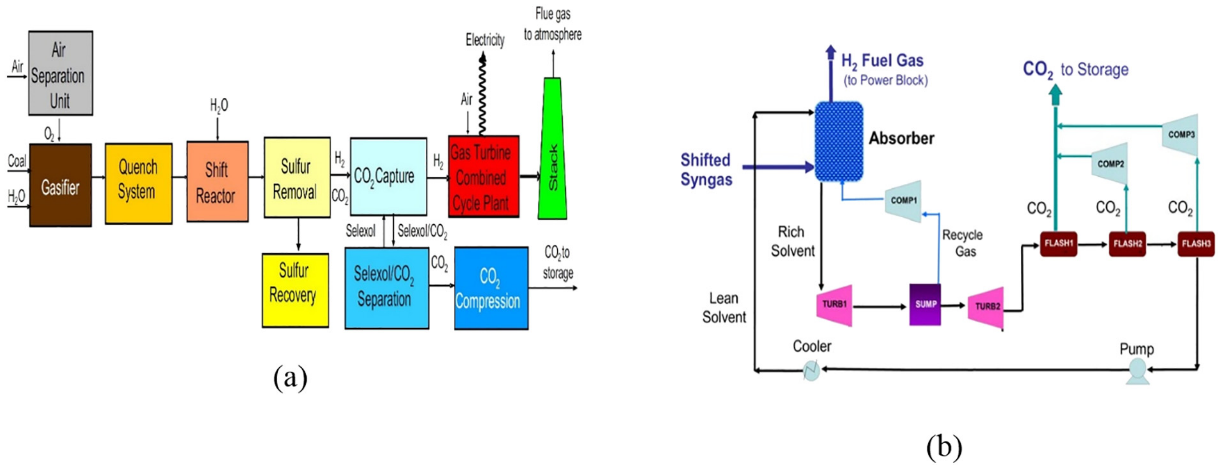


Fig. 3. A pre – combustion CCS Technology (Su et al., 2009).

combustion includes absorption physically, then releasing the CO_2 once the sorbent pressure drops, as depicted in Fig. 3(b), instead of using a chemical approach to trap the carbon dioxide like using amine systems in post combustion capture. The use of IGCC involves some limitations as there are some loss in energy during the carbon dioxide capture because of the shift reactor and other steps involves in this process.

It is also possible to use pre – combustion carbon dioxide capture in power plants that utilizes natural gas. Using natural gas as fuel involves conversion of the gaseous fuel to synthesis gas through reactions with O_2 often referred to as reforming. Concentrated carbon dioxide and hydrogen is produced (Romano et al., 2010; Martın et al., 2011; Schell et al., 2012; Casas et al., 2013; Jiang et al., 2015; Kang et al., 2015; Park et al., 2015a; Dai and Deng, 2016; Zheng et al., 2016; Lueking and Cole, 2017; Alonso et al., 2017; Zhang et al., 2019; Smith et al., 2012; Said et al., 2011; Stanger and Wall, 2011; Vellini and Gambini, 2015; Falkenstein et al., 2017). It must be noted that this method is very expensive compared to using natural gas as fuel but in post combustion capture approach.

2.3. Post- combustion approach

The post combustion carbon capture (PCC) absorbs the carbon dioxide produced by the flue miasma after fossil commodities or materials made of carbons undergo a combustion process. The greatest quantity of electricity used by the world in recent times is obtained from power plants that functions through a combustion process. The main process in coalfired power plants used today is the burning of coal fused with air in a boiler or a furnace (Metz et al., 2005). The process is an exothermic reaction and the steam released is used to run a turbine generator shown in Fig. 4.

The high temperature gases that flows out of the boiler is made up of nitrogen from air and water vapor in smaller concentrations. There is also carbon dioxide produced from the hydrogen and carbon from the fuel used. Sulfide dioxide (SO_2), nitrogen oxide (NO) and fly ash (particulate matter) are also formed due to the burning of impurities in coal. These toxic gases and others like mercury must be eliminated as they are considered as pollutants according to emission standards (National Research Council, 2010). In some situations, elimination of pollutants like SO_2 helps in the provision of pure gas stream for capturing CO_2 (National Research Council, 2010). Chemical reaction is described by scientists as the outstanding option for capturing CO_2 from flu gases of a pulverized coal plant but a solvent called monoethanolamine (MEA) is also required to facilitate the chemical reaction process. MEA is a member of the amine compound. The flue gas is first scrubbed in a vessel called an absorber. The absorber helps in the capturing around 85% to 90% of the CO_2 produced. CO_2 in a form of a solvent is injected into another vessel named as the regenerator or the stripper. In the second vessel, the release of CO_2 involves usage of

Table 1
Investigations being conducted on pre – combustion between 2010 and 2017.

Period	Strategy	Composition of the gas	Characteristics	Ref.
2010	Absorption Chemically	Synthesis gas	Several carbon dioxide capture methods were investigated. The outcome of the investigations was compared to amine solutions.	(Romano et al., 2010)
2011	Pressure swing adsorption	Carbon dioxide	Synthesis of polymers was conducted to support the adsorption of CO_2.	(Martın et al., 2011)
2012	Pressure swing adsorption	Carbon dioxide and Hydrogen	mesoporous silica MCM – 41was used	(Schell et al., 2012)
2012	Absorption Chemically	Synthesis gas	Solvent made up of K_2CO_3 were used for CO_2 sequestration from the synthesis gas	(Romano et al., 2010)
2013	Pressure swing adsorption	Carbon dioxide and Hydrogen	An extensive parametric study of a pressure swing adsorption process for carbon dioxide capture was investigated	(Casas et al., 2013)
2015	Adsorption	CO_2 as well as methane	Selectivity of CO_2 and methylene increased	(Jiang et al., 2015)
2015	Membrane	Carbon dioxide and hydrogen	MOF nanosheets were investigated for carbon capture.	(Kang et al., 2015)
2015	Absorption physically	Carbon dioxide, Hydrogen sulfide, carbonyl sulfide	A two stage per combustion carbon dioxide capture process was developed.	(Park et al., 2015a)
2016	Membrane absorption	Carbon dioxide and Helium	High carbon dioxide absorption capacity	(Dai and Deng, 2016)
2017	Gas separation by means of hydrate	Carbon dioxide and hydrogen	The CO2-H2-TBAF semiclathrate hydrate developed	(Zheng et al., 2016)

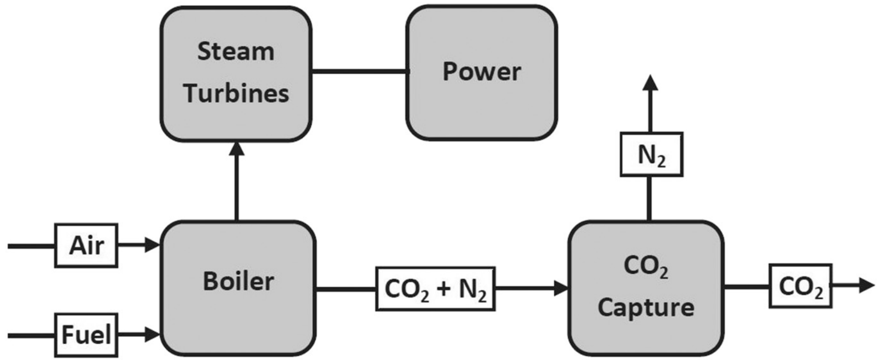


Fig. 4. A diagram showing post combustion carbon dioxide capture (Metz et al., 2005).

steam. The CO_2 produced after this process is highly concentrated (Solomon et al., 2007). The gas is compressed as well as conveyed to a location where they can be stored. The solvent used in the process is the forced back and recycled to the absorber. A detailed post combustion capturing of carbon dioxide is shown in Fig. 5 (Edmonds, 2008).

This technological approach is suitable for capturing carbon dioxide at pulverized coal power plant as well as at a natural gas fired boiler. Fig. 6 explains this methodology. The coal plants often have the flue gas carbon dioxide concentration being denser compared to the natural gas combined cycle, NGCC, but it is still possible to obtain high removal efficiencies even with the amine based capture systems (Metz et al., 2007). The natural gas has no impurities hence the flue gas stream is very clean. This implies that there will be no need for any cleanup for capturing the CO_2 effectively (Rao et al., 2004; Barchas, 1992). Table 2 captures the recent studies for post combustion in carbon dioxide capture.

2.4. Oxy–combustion approach

An option to post–combustion process, the oxy–combustion method has recently been developed as CO_2 capturing technology. This process uses pure oxygen in the combustion process and this reduces the quantities of nitrogen (Rubin et al., 2012; Wappel et al., 2010; Savile and Lalonde, 2011). Fly ash is also eliminated from flue gas stream resulting in the flue gas which only made up of CO_2 and water droplets as well as some impurities like sulfur dioxide. Compression and reducing the temperature of the flue gas is a medium used in the removal of the water vapor (Fauth et al., 2012). This process leaves behind pure carbon dioxide which is storage directly as shown in Fig. 7. One advantage of oxy – combustion over post combustion is the avoidance of an expensive CO_2 capture system for post combustion (Scholes et al., 2013; Zhang et al., 2014a). In place of a CO_2 capture systems for post combustion, the oxy combustion uses air separation unit (ASU) to produce clean oxygen with around 95% to 99% purity for oxyfuel systems compared to Integrated Gasification Combined Cycle plant of the same volume (Jayakumar et al., 2016). Air separation unit affects the cost significantly. Extra gas transformation is often required to limit the air pollutant concentration in order to meet the correct environmental guideline. This will further reduce a build of unwanted materials in the flue gas recycle (Jayakumar et al., 2016; Wang et al., 2016; Nwaoha et al., 2017; Wahby et al., 2012; Said et al., 2011; Stanger and Wall, 2011).

Temperature for burning using pure oxygen is greater than air hence oxy combustion involves huge portion of the stream for the flue gas

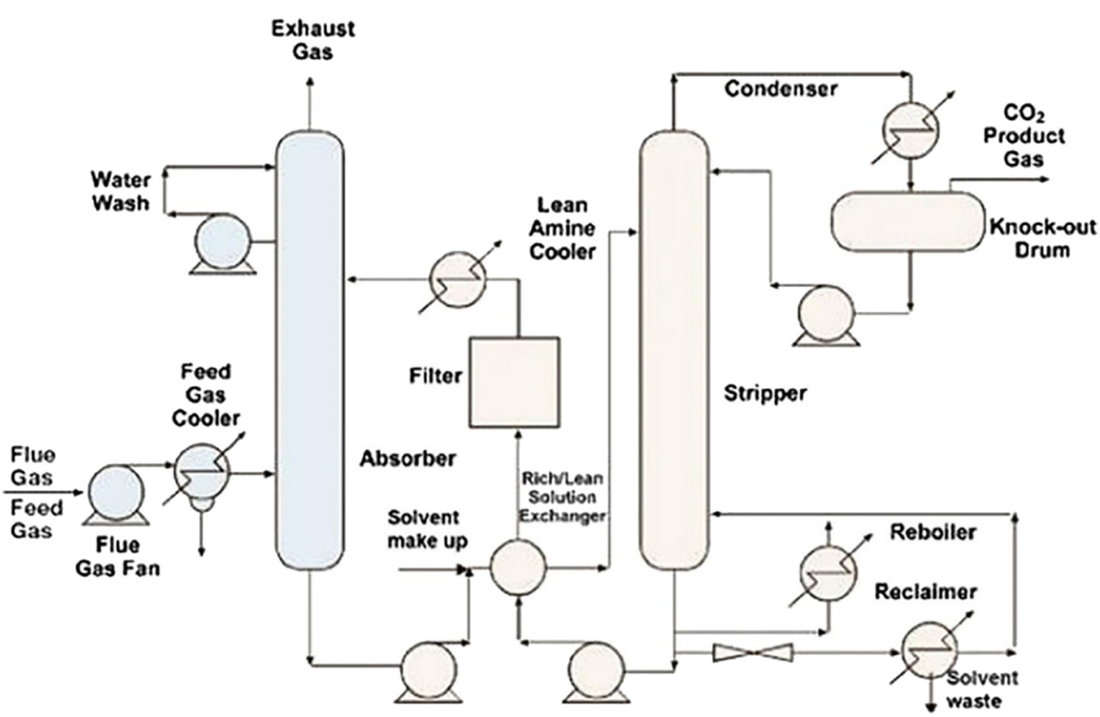


Fig. 5. Carbon dioxide capturing method using an amine type post combustion (Metz et al., 2005).

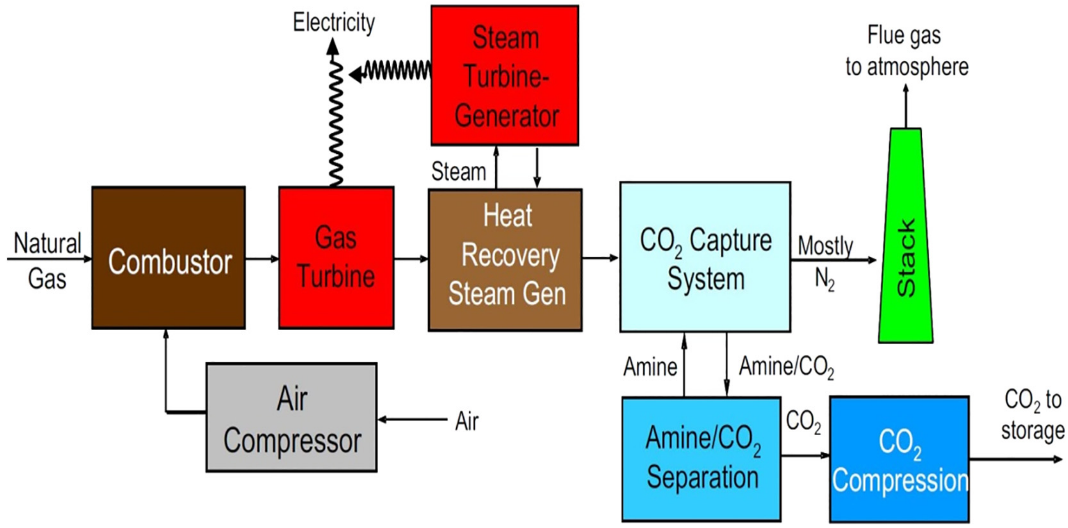


Fig. 6. Diagram showing an amine based post – combustion CO_2 capturing system for NGCC (Metz et al., 2005).

being used back in the boiler to maintain optimal operating temperature. Recent oxy fueled boilers come in designs to reduce recycle using slagging combustors or non – stoichiometric burners. Sealing of the system is another important stage in the design to maintain the needed oxygen and nitrogen found in the gas. Sealing prevents air leakages into the flue gas. This is considered as one of the most difficult maintenance issues because the leakages at the flanges and joints are difficult to prevent especially along the flue gas duct (Vellini and Gambini, 2015). There has been several research work conducted on 30 MW thermal plant that uses the oxy combustion technology. Oxyfuel systems requires gas treatments to eliminate pollutants from the system and this reduces the efficiency of the system to 90%. It is possible to apply the concept of oxy combustion in a simple cycle. Table 3 also shows some current research conducted using the oxy combustion technology. Fig. 8 shows the CCS technology as well as sources from different commodities like cement, steel production and bioethanol plants. The bioethanol plants produce food grade carbon dioxide from fermenters. This investigation explores the main technological advancement made in recent times with respect to carbon capture (Falkenstein et al., 2017). Table 4 shows some recent advancement made in this technology.

2.5. Comparison of the various carbon capture capacity between 2006 and 2018

Carbon capture and storage involves large sequestration of CO_2 from well-known origins followed by separation from the atmosphere as well as its usage in futuristic terms. It is a solution designed for a situation where high emissions of carbon dioxide due to high energy consumption and high dependency on fossil commodities becomes unavoidable. It is a suitable approach for carbon separation from high CO_2 plants. Well known areas where carbon capture and storage can be utilized are generation plants and manufacturing divisions. From Fig. 9, the carbon emissions is likely to exceed 32.27 billion tonnes by 2018. Researchers anticipates that by the year 2020, this quantity of CO_2 emissions is likely to increase appreciably to 35.63 billion as well as 43.22 billion by 2040. This increase according to researchers will emanate largely from developing countries. 33.4 million tonnes of CO_2 can be captured annually in spite of all the carbon capture and storage facilities across the world. This is 0.09% of the total projected carbon emissions. To combat climate change, expansion of CCS technology will be a necessity.

Table 2
Post combustion carbon capture.

Year	Methods	Gas component	Brief description	References
2010	Pressure swing adsorption	Presence of flue gas	Nearly 98% of pure carbon dioxide was obtained after a synthetic process using pressure swing adsorption.	(Rubin et al., 2012)
2010	Ionic liquid	–	Ionic solvent was used for the absorption of CO_2	(Wappel et al., 2010)
2011	Biotechnology	–	The process of post combustion CO_2 capture can be made faster through usage of carbonic anhydrase according to this research work.	(Savile and Lalonde, 2011)
2012	Adsorption	Carbon dioxide and Helium	The work concluded that mixed – amine polyethyleneimine (PEI) as well as 3 – (aminopropyl) triethoxysilane are very good sorbent of carbon dioxide.	(Fauth et al., 2012)
2013	Cryogenic separation of the membrane	Carbon dioxide and Oxygen	With a cost of 35 dollars per ton, the new membrane – cryogenic was described cost effective	(Scholes et al., 2013)
2014	Adsorption of the membrane	Carbon dioxide and nitrogen gas	A numerical research was conducted to determine the impact of membrane as well as contractor properties on carbon dioxide capture using methyl diethanolamine and 2-1- piperazinyl- ethylamine solvents.	(Zhang et al., 2014a)
2016	Adsorption	Carbon dioxide and Nitrogen gas	An investigation was conducted to determine the effect of carbonization reaction mechanisms for carbon dioxide and potassium carbonate.	(Jayakumar et al., 2016)
2016	Adsorption	Carbon dioxide and Nitrogen gas	An investigation was carried out to explore the possibility of capturing CO_2 using PEI – impregnated, millimeter sized mesoporous carbon spheres.	(Wang et al., 2016)
2017	Chemical absorption	Carbon dioxide and Nitrogen gas	The carbon dioxide were captured using formulated, reactive, blended amine solution.	(Wahby et al., 2012)

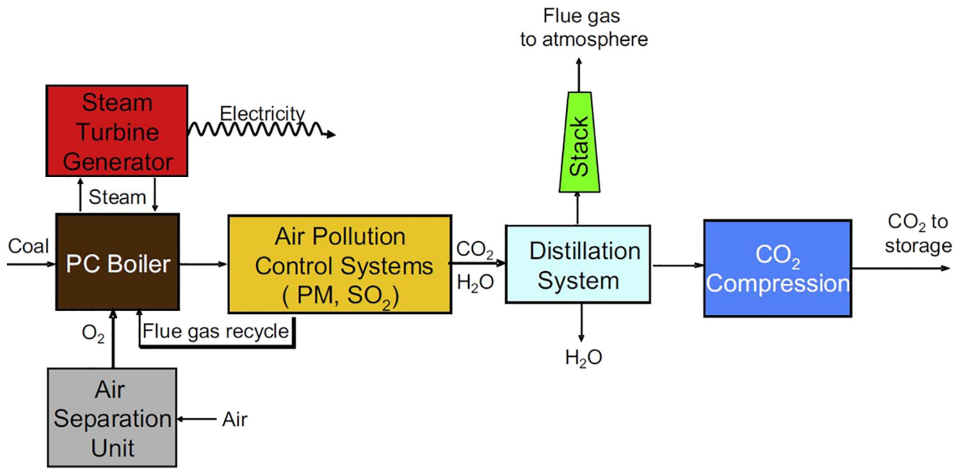


Fig. 7. Oxy – combustion technology utilized in a coal fired power plant (Rubin et al., 2012).

From Fig. 9, it is observed that between the year 2006 to 2018, the number of commercial carbon capture facility for post combustion has surged up from from 16 to 30. This indicates a high increase compared to pre combustion. It therefore explains the increase in carbon capture capacity from 26,000 tonnes per day in 2006 to 50,000 tonnes per day in 2018. Pre – combustion was nearly zero between 2006 and 2014 but after 2014, the capacity has increased to nearly 7000 tonnes per day in 2018. Table 5 also captures other technology for carbon capture but with insufficient large scale experience.

Table 6 captures comparison between the three main CCS technologies; post combustion, pre-combustion and oxyfuel combustion. Fig. 9 explains projected values for commercialized CCS across the world. From Table 6, it is observed that oxyfuel combustion capture system presently has no carbon capture storage. Most established CCS technology is the post combustion technology. Researchers are also investigating on solid sorbent technologies in order to improve their performance. Pre-combustion technology is described as the best alternative to mitigate this challenge. A clear comparison for all the three types of CCS technology is shown in Table 6.

2.6. Transportation and storage of captured CO_2

The captured carbon dioxide always needs to be transported from the capturing site to the storage site. The key consideration that should be taken during the transportation of carbon dioxide are the compression of the gas to a supercritical state, pipeline corrosion and the effect of fluid composition on the power that will be consumed (Hussain and Hägg, 2010; Sreedhar et al., 2017; Abu-Zahra et al., 2013; Global CCS Institute, 2010; Rubin et al., 2007; Global CCS Institute, 2013; Cousins et al., 2011; Maitland, 2016; Khalilpour et al., 2017; Sanchez Fernandes et al., 2016; Mac Dowell and Shah, 2014; Ho and Wiley, 2016; Maitland, 2016; Khalilpour et al., 2017). This can be achieved by recompressing the pipeline at distance beyond 150 km. Transporting the carbon dioxide using pipelines in bulk reduces the overall cost of the carbon capture and storage system. This is considered a matured technology in the carbon capture and storage system. For over 40 years, this technology has been adopted in the transportation of 50 Mtpa carbon dioxide via 3600 miles (Borhani et al., 2015a). Sharing the transportation network is one method of reducing cost. An in depth knowledge on the thermodynamic and transport characteristics of carbon dioxide mixtures is very necessary when designing a carbon capture system. Majority of the overall cost for the transportation and storage of the carbon dioxide in a carbon capture and storage system occurs at the compression stage of the carbon dioxide stream. An attempt to capture carbon dioxide at higher pressure reduces the compression power at downstream.

In the last few decades, several geological sites have been used for storing CO_2 such as saline aquifers, depleted basins and enhanced oil recovery (Borhani et al., 2015b). There are some requirements for any storage sites to be suitable for storing CO_2. The formation of the site must be porous and permeable for easy injection of huge volumes of carbon dioxide. Also, it must have rock caps for the imprisonment of the carbon dioxide and prevention of any potential leaking. Storing carbon dioxide in an abandoned oil field is also appropriate because most of these sites become impermeable after holding oil and gas for several years. These reservoirs have some disadvantage as well as they are often penetrated by other wells damaging the seal. Retaining the carbon dioxide carbon dioxide is achieved through a trapping mechanism: a) stratigraphic and structural (primary trapping occurs beneath seals of low seals of low permeability rocks, dominant at early stage); b) residual (Using water capillary pressure, trapping is achieved via rock pores c) Solubility (residual gas trapping) and d) mineralization (changing the pore – space topology and connectivity). There is precipitation of carbonates at the last stage of the storing process and this is likely to block the pathway for the fluid and there is also finally a loss of the storage pore volume (Borhani et al., 2015b).

Table 3
Recent investigation using oxy combustion technology (Vellini and Gambini, 2015).

Year	Methods	Gas component	Brief description	References
2011	–	Flue gas	Carbon dioxide capture using integrated oxy combustion and $Mg(OH)_2$ was investigated.	(Wahby et al., 2012)
2011	–	Flue gas	The impact of sulfur on the capturing of CO_2 via a process using oxy combustion was researched.	(Said et al., 2011)
2015	Oxygen transport membrane	Flue gas	An investigation into the characteristic efficiency of steam cycle power fitted with a carbon dioxide capture using oxy fuel combustion was thoroughly investigated.	(Stanger and Wall, 2011)
2016	Oxygen transport membrane	Flue gas	Carbon dioxide selectivity as well as well as permeability of oxygen was investigated using oxygen transport membrane reactor. The membrane reactor showed high carbon dioxide absorption of 87.1%.	(Vellini and Gambini, 2015)

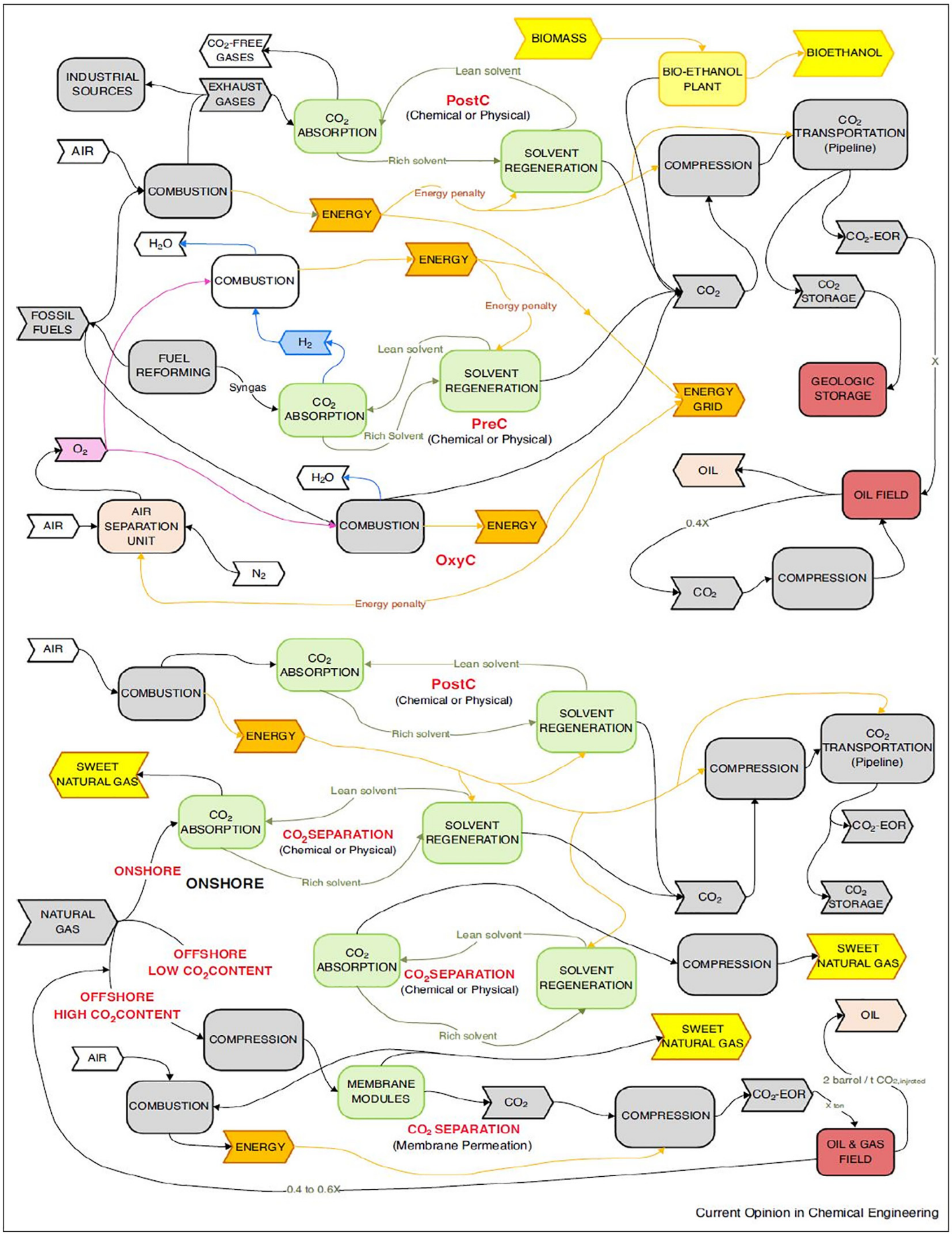


Fig. 8. Recent advancement of carbon dioxide capture routes (Rubin et al., 2012).

Other researchers investigated the direct relationship between injection and induced seismicity for a long term and concluded that this storage process could lead to earth quakes but the leakage of carbon dioxide is not a major challenge in terms of scaling up carbon capture and storage systems. The cost for the injection is approximately 0.5–8 $/$tCO_2$. A combination of enhanced oil recovery with a storage system will reduce the overall cost.

3. Application of the various CCS technologies

For commercial and industrial power plants, post-combustion carbon dioxide capture is considered the matured type of technology compared to the others. Using solvent for the carbon dioxide capture is very important in post-combustion in the capture of carbon dioxide. Today, researchers are also exploring the various type of solvent, design and an integrated solvent design for the capture of carbon dioxide. Other investigations into the selection systematically and design of solvent for post-combustion carbon dioxide capture using several predictive methods have all been explored (Al-Marzouqi et al., 2008; El-Naas et al., 2010). Several computational and statistical strategies have all been used during the investigation. For instance, the fluid theory family approach and quantitative structure property relationship have all be utilized during the conduction of an investigation (Zhang et al., 2014b; Joel et al., 2014). Using universal quasi – chemical functional group activity coefficient approach has been designed for the capture of carbon dioxide (Wang et al., 2015). Other researchers attempted the possibility

Table 4
Technologies for carbon dioxide capture (state of the art technology at commercialization).

Technological advancement	Merit	Obstacle and literature gap	Ref
Absorption via chemical means	It is considered a matured kind of technology for post combustion. It is also suitable for power plants fired by carbon. The efficiency for capturing the carbon dioxide is very high and losses with respect to hydrocarbons is low.	The capture ratio and heat ratio are very high. For power plants operated using coal, there is high capture energy penalty of approximately 20–30%. Challenges relating to corrosion is also a major obstacle. Solvent challenge relating to stability, reduction in capture ratio, heat ratio and stripping temperatures to facilitate the usage of waste heat.	(Falkenstein et al., 2017; Agarwal et al., 2010; Wappel et al., 2010; Savile and Lalonde, 2011; Novek et al., 2016; Rochelle, 2012; Ampomah et al., 2017; Idem et al., 2006)
Physical absorption	Has high capture efficiency. Very suitable for power plants fired by coal. The capture efficiency is very high but the heat ratio is low for regeneration. This is also considered a matured technology for processing of natural gas and post combustion.	The selectivity is low with high hydrocarbon losses.	(Idem et al., 2006; Leung et al., 2014)
Membrane penetration	Suitable for natural gas processing on large scale. Does not require any chemicals.	Confining of natural gas is needed. There is high hydrocarbon losses	(Olajire, 2010; Baker and Lokhandwala, 2008; Kim and Lee, 2013)
Pre combustion	Appropriate for power plants fired by coal. Cost effective, suitable for hydrogen production in commercial quantities. Has highly efficient, approximately 10–15% low capture energy penalty.	It is very complex, requires new materials for high carbon dioxide capture at high temperature, huge capital expenses, still undergoing developmental processes. The experience for large scale hydrogen fired power plant is still inadequate	(Lock et al., 2015; Grasa and Abanades, 2006)
Cryogenic distillation	This is also a matured technology for natural gas with high carbon dioxide composition, high selectivity, little hydrocarbon losses. There is no need for compression as the carbon dioxide is obtained in liquid state hence transportation is easy and simple. Suitable for high carbon dioxide composition.	Avoiding the carbon dioxide freeze out is very necessary and also refrigeration energy penalties.	(Idem et al., 2006)

of adding the solvent selection process with the carbon dioxide capture process (Lampe et al., 2015; Zarogiannis et al., 2016; Papadopoulos et al., 2016; Matsuda et al., 2007; Venkatraman et al., 2016; Chong et al., 2015; Mac Dowell et al., 2010; Bardow et al., 2009).

For renovation of existing power plants, post combustion carbon dioxide capture is considered the best of options. This method has thoroughly been investigated as a medium of enhancing the performance of any equipment. As explained earlier, several numerical studies and modelling research work has been conducted using the approach (Stavrou et al., 2014). Due to the gas volume being low, pressure being high and the amount of carbon dioxide also being high, less energy is often required for pre combustion carbon dioxide. Less amount of water consumption is observed for pre-combustion compared to post-combustion. An alternative fuel generated for pre-combustion is hydrogen/syngas (Stanger et al., 2015). The oxyfuel – combustion is considered more environmentally friendly compared to the other two methods. There is no need for any operations being done chemically for this types of carbon dioxide capture technology and also suitable for several types of coal fuels (Borhani et al., 2016; Elwell and Grant, 2006; Wang et al., 2011; Borhani et al., 2015c; Pfaff and Kather, 2009). It is simple to renovate it compared to the other types like the post-combustion capture system. This approach has high efficiency in terms of carbon capture. Some advantages of this type of carbon dioxide capture technology is the fact that the equipment size is reduced, the air separation technology is high, it is well suited for conventional, efficient steam cycle with less modifications and the removal of NOx control as well as the carbon dioxide separation stage makes it very advantageous (Adjiman et al., 2014; Bardow et al., 2010; Adanez et al., 2012; Markewitz and Bongartz, 2015; IEA, 2007; IEA, 2008; Vatopoulos and Tzimas, 2012).

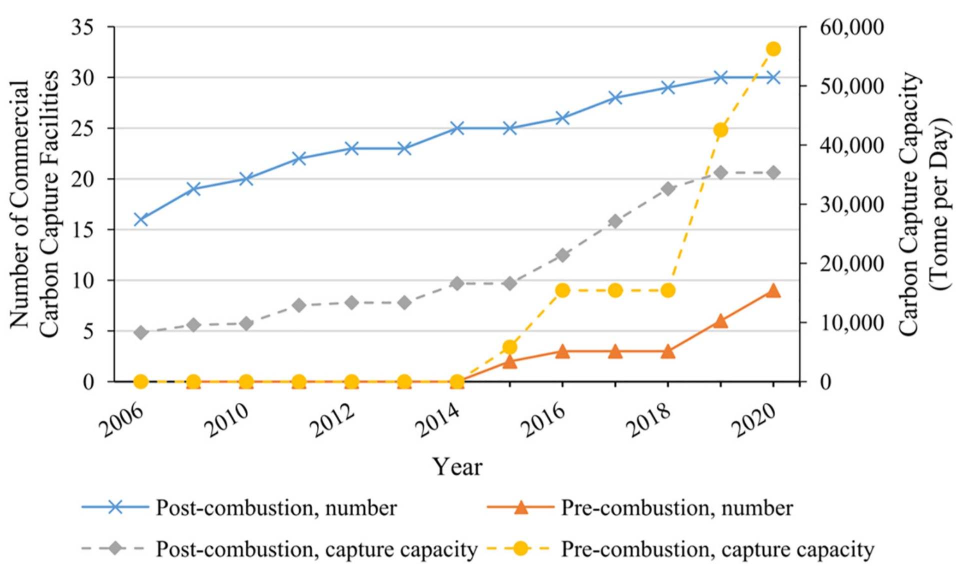


Fig. 9. Commercialized carbon capture technology across the world (Wappel et al., 2010).

Table 5
Other technology for carbon capture but with insufficient large-scale experience.

Technological advancement	Characteristics	Merits	Ref
Hybrids	High carbon dioxide elimination via cryogenic distillation.	The cost is very low, and the capture energy penalty is low as well	(Hanak et al., 2015)
Enhancement of chemical or physical absorption	Flowsheets are complex and requires mixed solvents.	The equivalent work needed is 12% less compared to a stripper. There is high heat ratio reduction because of the usage of the mixed solvents instead of MEA in liquified state. The thermochemical stability is very high.	(Dunstan et al., 2016)
	The solvents have high efficiency	Reduced heat ratio	(Dong and Jin, 2012)
	Hybrid solvents	The challenge in relation to high parasitic energy consumption regarding water is reduced.	(Luo et al., 2016)
	Requires solvents that are anhydrous.	Reduced heat ratio, reduced evaporation losses.	(Gervasi et al., 2014) (Park et al., 2015b)
	Ionic liquid	Reduced heat ratio, loading of the carbon dioxide results in phase change.	(Kim and Lee, 2017)
	Solvents that undergoes phase change	Requires using recycled heat	(Bara et al., 2010)
	carbon dioxide solventing out requires adding other solvent that are inert	Low heat ratio	(Rochelle, 2012)
	Solvents that are organic		(Brennecke and Gurkan, 2010)
Membrane penetration	New membrane materials	High flux but the exhaust gases have low pressure but high carbon dioxide.	(Gomez et al., 2014)
	Integrated membrane material as well as process development for gas separation	Sustainable membrane permeability	(Pinto et al., 2014; Arshad et al., 2016)
	Multi stage schemes		(Shen et al., 2017)
	The sweep agent used is steam.	Highly efficient	(Novek et al., 2016)
	Solvent supported membrane	Efficient permeate elimination, avoiding carbon dioxide buildup,.	(Du et al., 2011)
		Volatility of solvent negligible (ionic liquids and deep eutectic solvents) to enhance selectivity.	(Caro, 2011)
Gas liquid membrane	Characterization and performance of various membrane materials	Highly efficient,	(Lin, 2015)
Adsorption	Novel sorbent materials	High surface area.	(Gervasi et al., 2014)
Oxy combustion	Makes post combustion capture simplified and also very efficient.	Highly efficient	(Lin, 2014)
Chemical looping burning	Uses metal oxide	Lower capturing energy cost	(Ramasubramanian and Ho, 2011)
Mineralization	Converting solid material	Commercialized	(Hussain and Hägg, 2010)

3.1. Capturing of carbon from exhaust gases

There is always a capturing energy penalty of 15% to 30% for power plants operated using carbon and this contributes to almost −85% of the carbon capture and storage expenditure (Intergovernmental Panel on Climate Change, 2005). To develop a carbon fired plant with an efficiency of 33% involves decreasing the power output by 1/3 and this increase the capital expenditure to approximately 77% (Dooley, 2006). Power plants fired by carbon have varying carbon dioxide emissions because of the variation in the fuel used but power plants fired by coal produces 1116 gCO_2/KWh at 30% and 669 gCO_2/kWh at 50% efficiency (Web.mit.edu, 2018). Even though coal is considered carbon dioxide intensive option, expansion in terms of capacity shows that initiatives for carbon mitigation are low compared to the economic incentives for a relatively cheap fuel. In terms of capital expenditure, natural gas fired power plant is better than power plants fired by coal since half of the capital expenditure for coal fired power plant is required for natural gas powered plant (US DOE/NETL, 2007). The overall performance uncertainties are estimated probabilistically (International Energy Agency, 2013). Uncertainties with regards to the capital expenditure are very high at an approximated value of 40% although variability has little influence on the levelized cost of energy (LCOE) (MIT, 2007).

Table 6
Comparison of the various carbon capture technology.

Technical issue	Post combustion capture	Pre-combustion capture	Oxyfuel combustion capture
Maturity of Technology	Matured type of technology utilized in many well-known applications at commercialized level	Dominant in process industry. Carbon capture and storage plants on full scale under progress.	There are presently no full scale oxyfuel carbon combustion and storage plant operating.
Merits	Very suitable for reconstruction of plants already in existence and this helps in consistent usage of common power plant generating technology like pulverized coal. There is also extensive research to enhance the efficiency of energy obtained from post combustion carbon capture equipment	The CO_2 separation process is less energy intensive because of low gas volume, high pressure and high carbon dioxide concentration. Acid gas removal process presently are used in several technologies commercially. The water consumption for this technology is also low compared to post combustion capture.	Pollutant is reduced. There is also no need for chemical operations on site. The technology is robust implying that it is compatible with other type of fuels. It is also easy and simple to reconstruct.
Demerit	Separation constraint due to low CO_2 partial pressure in flue gas.	High energy loss because of sorbent regeneration.	Net power output reduced.
Capital	Very expensive technology in terms of cost of operating the system.	IGCC cost is more than that of coal plant.	Technology for separating air very expensive

This shows that the operational costs (OPEX) determines the overall cost of carbon capture and storage. Other investigators reported that post combustion capture of carbon dioxide capture using chemical absorption is the most effective and cheapest means of carbon capture and storage technique (Fossiltransition.org, 2018). The main obstacle is heat demand which increases the operational cost and this also reduces the power capacity. Power plants fired by carbon via hybridization using solar aided post combustion improves the overall efficiency of the plants. There is limitation in terms of the driving force for state of the art membrane permeation compared to chemical absorption in the capture of carbon dioxide from exhaust gases (Zhang et al., 2018a). The reliance of fossil commodities when using coal fired plants can be replaced using renewable energy and this will reduce the fossil commodity that will go into combustion. The energy obtained from renewable energy being intermittent implies that the unit for capturing the carbon must be flexible in order to enhance the economics of the carbon capture. Flexibility is obtained by storing the solvent, removing energy generation from the capture of carbon dioxide to meet energy prices at peak times (van der Spek et al., 2017). The flexibility of capturing unit helps in reducing the capital expenditure to 28% (Zhang et al., 2018b). Capture energy penalty is reduced due to variable capture aligned to energy demand and dispatch and this often leads to increasing net efficiency and capacity (International Energy Agency, 2013). A practical example is the absorber sized for a time average condition cost approximately 4% less than when it is sized for peak energy generation (International Energy Agency, 2013).

3.2. Carbon dioxide capture from natural gas

Similar to post combustion, natural gas is also dominated by precisely physical absorption (Philibert, n.d.). Natural gas processing for Floating Production Storage and Offloading (FPSO) is slightly different from other natural gas processing. For natural gas processing of FPSOs, small area creates a technology niche for membrane permeation because it has low foot print and modularity. For instance the first PFSO started operation in 2010 for the Brazil pre sal oil and gas field (Philibert, n.d.) and they used membrane separation for separating carbon dioxide. Seven PFSO were being operated actively in 2016 (Mac Dowell and Shah, 2014) and six out of the seven were functioning via membrane permeation with each processing approximately 4–7 MMscmd of natural gas with almost 20% of carbon dioxide (CDM Executive Board, 2012). One of the key factors for the selection of natural gas processing technology is the partial pressure of carbon dioxide in raw natural gas and plant location. Chemical absorption is suitable for low carbon dioxide feed that is less than 20% because higher carbon dioxide content increases solvent recirculation rate and heat duty. Membrane permeation is best suited for medium to higher carbon dioxide partial pressure compare to chemical absorption. Other high carbon dioxide content project could be found in pre -salt field in Brazils' offshore pre oil field (Libra: 48%, Jupiter 78%) and La Barge gas field in Wyoming in the United States but these projects function using cryogenic distillation. The main merit of these projects is the fact that the carbon dioxide produced comes in liquid form which helps in their easy transportation via a pipeline but this advantage come with some challenge as well. When temperatures are low and the liquid is being operated at higher pressures, the carbon dioxide may freeze out and this will required the need for other complex technology like the Ryan Holmes process (Zhang et al., 2018b; International Energy Agency, 2013; Philibert, n.d.; CDM Executive Board, 2012). Today, the scientific community has explored several innovative means of gas and liquid transportation like the Ormen Lang project where natural gas and monoethylene glycol as anti-hydrate are transported via two subsea 120 km pipelines (Maitland, 2016). Natural gas in their raw state today can be channeled to an onshore facility for the separation of the carbon dioxide and fractionation of natural gas liquids and the carbon dioxide piped back to an offshore facility (International Energy Agency, 2013). Hybrid processes often uses cryogenic distillation for huge separation, reducing carbon dioxide composition so that chemical or physical absorption can be implemented (Philibert, n.d.). Another research conducted was hybrid natural gas processing using membrane permeation for higher removal and chemical absorption (CDM Executive Board, 2012).

4. Sustainability and socio-economic aspects of CCS technology

Fossil fuel contributes to more than 80% of current world energy demand (Philibert, n.d.; CDM Executive Board, 2012; Owusu et al., 2016). It is expected that this estimated figure will drop slightly to 75% by 2035. It stipulates the importance of meeting the world energy consumption without further destruction to the environment. As explained earlier, a method of meeting this high global energy demand is through the application of CCS technology. This approach will aid fossil commodities form part of long-term energy mix. Emissions produced from fossil fuel will drastically be reduced as a result of the introduction of CCS technology. CCS can further sustain the world's high dependency on fossil products in order to meet its' demand. Fossil fuel will surely dominate the worlds energy generation medium in the next couple of years (Sarkodie et al., 2019; Asumadu and Strezov, 2019; Sarkodie and Strezov, 2019; Sarkodie and Strezov, 2018). It will safely secure supply of energy without emissions of toxic substances into the atmosphere. CCS can therefore help in global sustainable development because the world energy demand can be achieved without causing harm to the atmosphere.

4.1. Environmental contribution of CCS to sustainable development

One fundamental principle of sustainable development is the ability to support biodiversity as well as the ecosystem (Owusu et al., 2016). The effect of CSS technology on the environment is very important. This is often determined by a constant observation of air, land, water and natural resources. Biodiversity, ecosystem and land for cultivation of crops are sometimes affected due to the implementation of such CCS projects (Akhtar and Sarmah, 2018a; Akhtar and Sarmah, 2018b). In instances where transportation route are developed via farmlands, food production might reduce. Relocation becomes eminent in some projects in order to develop safe and good infrastructure. Sea life is also sometimes destroyed, making the ecosystem very vulnerable (Fan et al., 2011). This is often the case for onshore and offshore projects. This can lead to reversed biodiversity because of the effect on ecosystem and habitats. Risk assessment for application of CCS must also factor into consideration damage of the CCS facility as well as the surrounding environment. Identifying the effect of CCS project on the environment is very necessary. Leakage of CO_2 is another issue related to CCS projects. The leakage of the stored CO_2 as a result of transportation can destroy groundwater, plant life and soil quality. Exposure to high amount of CO_2 can ultimately lead to death. In 2012, Scotland investigated the effect of CO_2 leakage on marine habitat. The investigation concluded that some species reacted negatively as result of an increase in CO_2 (Shackley and Verma, 2008).

4.2. Social contribution of CCS

An introduction of CCS in most fossil related projects will increase the number of skilled personnel needed in maintaining the project. It will therefore create more jobs hence improving the livelihood of people. The daily operation of the plants will demand more hands and the storage site will also require consistent observation and monitoring. This will be a job creation avenue for years. Building of the infrastructure will also create jobs even though that might be for a short period of time. It will also support local communities to train more people. An increase in job creation will stabilize the world economy (Viebahn et al., 2007). Employees will be guaranteed long term jobs which will improve their standard of living. Siting a project in an area where the rate of unemployment is high will help improve the standard of living of the

community. It will therefore serve as poverty alleviation programme. The poverty level will also reduce drastically once more jobs are created. Work environment will be safer due to the implementation of the technology once project participants agree to join health and safety procedures.

4.3. Economic contribution of CCS technology

Producing natural resources can support the energy sector and improve the economy of most countries especially developing countries (Zhang and Li, 2008). Application of CCS on fossil related projects will significantly improve the climate change of the country where the project is installed. The energy that is generated from such advanced related projects is usually clean (Keith et al., 2006). The cleaner the energy, the more attractive they become on the energy market. Incentives from energy systems with CCS can be made higher compared to that of projects without CCS. This will enhance the advancement of CCS related projects further and also boost the economy of the country. From literature, an explanation is given that integration of CCS on energy related projects will make it attractive to the energy market hence increasing the amount of investment into the sector. The carbon foot prints from fossil product is reduced as a result of the integration of CCS technology to the system. This is one key contribution of the application of CCS that convinces investors to invest money into this novel technology. In summary CCS technology can be described as a vital climate mitigation tool and also an approach of meeting the world energy demand (Seevam et al., 2008).

5. Current status and policies of CSS technology around the world

Most policies formulated in the implementation of CCS on fossil related projects are centered around the transportation and storage of the CO_2. The European Union till date has the most relations on CCS technology (IEA (International Energy Agency), 2008). Conventions on CCS technology are categorized into two main sections; the first one considers CCS an option aiding in the reduction of emissions (Nations Framework Convention on Climate Change, Kyoto Protocol); whereas the second one concerns regulations on oceanic sequestration for captured CO_2 (United Nations Convention on the Law of the Sea, London Convention).

5.1.1. USA and Australia

Research activities in CCS have surged up over the last decades in the US due to government plan for providing 2.4 billion dollars to support CCS projects and investigations. According to the American Clean Energy and Security Act, implementation of CCS should provide around 26% emission reduction from industries (IPCC, 2001). The geological salt water reservoir was developed from the CCS state league. The CCS flagship project was also developed in Australia and this provided two billion dollars for research into CCS. This further led to the formation of the global CCS institute with the main objective of advancing the development of CCS technology (Coninck et al., 2008).

5.1.2. EU

The European Union (EU) has strong commitment to combat climate change and for this it exhibits commitment towards the advancement of CCS technology, as shown in Table 7. CCS is considered on the high priority development goals by the EU but some of the member states are still struggling to keep up with targets and standards set by the EU. The EU has a legal framework on the development of CCS (EC (European Commission), 2006a). The European Commission (EC) considers CCS as the possible solution to emission released from fossil fuel related projects and this according to the commission, is the future of the energy industry in terms of energy security and climate change

Table 7
The European Union policies on carbon capture technology.

Classification of policies	Policy	Explanation in terms of carbon capture
Policies relating to industries	1. Interventions relating to climate change	The European Commission explains that the integration of CCS in energy system will aid the European Union meet 15% of its emissions targets. This can only be achieved provided CCS gets the necessary support. The commission has several pilot projects on CCS with the main objective of extending research work in this novel technology. Again, the commission is giving out financial support under the EU policy Framework) to support in easy commercialization of CCS technology.
	2. Geological Storage of carbon dioxide	The European Union has also passed several policies and regulations relating to the safety of storage sites.
Policies related to research activities	1. Energy technology strategy	The European Union has directives towards generating sustainable, safe and cheap energy. The Union also supports fast commercialization of low carbon technology by giving financial support to research activities geared towards CCS. Developing efficient capture technology (ENCAP) is another major priority of the European Union.
	2. Seventh Framework programme	Leadership Forum (CSLF), Cooperation Action within CCS (China – EU (COACH), Regulates activities for activities leading to carbon capture and storage (STRACO$_2$), European CO_2 geography network, zero emission for EU fossil power generations before 2020 (ZEP).
	3. Research fellowships	UK: Near Zero Emission coal (NZEC)
Competition policies	1. Proposal for the geological storage of CO_2	This intends to prevents monopolization of CCS by some entities in the European Union. The directive states that members belonging to the EU must have free access to the CO_2 transport network and storage sites.
	2. EU Energy market reform	Most future applications for CCS will be directly linked to the power sector and further advancement of the power sector will contribute to the fast commercialization of CCS.
Policies relating to export	1. Zero emission platform	The European Union projects that most of the carbon emission will originate from India and China futuristically hence there is the need for a strong collaboration between the EU and these countries. International relations will help in reducing climate change and also support the advancement of CCS technology.
	2. Aid EU industry to access foreign markets	The EU serve as a backbone for it's industry in gaining access to foreign markets. Some of the collaborative projects is achieved via international relations. Eg. Alstom, Bp, Doosan Babcock and shell are participants of the EU – China NZEC project
European Union policy impact analysis and CCS	1. Review of sustainable development strategy	The European Union suggests that introducing policies related to renewables and CCS will require creating public awareness as well as the decision-making being fast.
	2. European Union impact analysis system	CCS technology according to impact analysis has uncertainties in terms of the impact on energy portfolio, interaction with renewable policies as well as technology needs outside the European Union.
	3. Environmental assessment directive	The approach adopted in the evaluation of strategic environmental impacts of CCS remain uncertain.
	4. Environmental impact analysis	Environmental impact analysis is aimed at specific project evaluation and it has been applied to evaluate CCS demonstration projects.

challenges. In 2008, EC implemented the Directive on the Geological Storage of CO_2. This eventually became the legal framework for carbon dioxide geological storage. The policy stipulated that new power stations must support the capture of CO_2 as well as all power stations that run on coal being retrofitted with CCS by 2020. There are other directives issued by the EC like the requirement for CCS equipment (Directive 85/337/EC), requirement for storage sires (Directive 200/60/EC, Directive 2004/35/EC). The EC in 2012 amended the European Union Emission Trading Scheme to include CCS technologies. Some of these amendments were the role of CCS technology, explanation of auction and quota and accommodate new investment in CCS R&D. The Emerging policy documents for CCS demonstration in developing countries was also developed in 2009. Some incentive policies rolled out by the EU include reducing operational expenditure for CCS (EC (European Commission), 2007).

The EU has many policies related to CCS technology but these policies face some challenges. CCS technology is currently yet to attain full commercialization hence overcoming these challenges relating to some of the policies is difficult. Management of storage sites in terms of risk assessment still poses a challenge to the EU. The policy on the geological storage of CO_2 explains that the license of any entity will be revoked whenever there is leakage of $CO_{2,}$ but the policy does not indicate measures put in place during the process of the leakage occurring. Strategies to determine responsibility for an entity's negligence in the event of any leakage is yet to be determined and this has a serious effect on storage sites (EUIAB (European Union Impact Analysis Board), 2007). Challenges relating to storage sites indicates that the capture of carbon dioxide, transportation and storage cannot be guaranteed hence reducing the potential of CCS becoming commercialized.

6. Challenges and future prospects of CCS technology

China has laid down target to reduce CO_2 emissions by 40% to 45% in 2050. A paradigm shift of the economy and selecting efficient emission reduction approach will make this a reality and with coal being one of the main sources of energy generation, integration of CCS into these projects will reduce the overall emissions from their energy sector (Socolow et al., 2004).

CCS technology is built to capture emissions from fossil related projects. It has the capacity of absorbing 85%–95% of CO_2 emissions. It implies that if more than 50% of thermal power has CCS integrated into the system, the power sector can reduce nearly a billion to of CO_2. The application of CCS will support the dependency of fossil fuel as a source of energy generation without toxic emissions into the atmosphere.

However, the application of CCS in the energy industry has some notable limitations as CCS involves higher energy consumption by the project in terms of capturing the CO_2 as well as compression of the gas. This may reduce the energy conversion efficiency from 48% to 36% once the CCS is installed. For example, if 50% of domestic thermal power has CCS integrated in them, the energy sector will utilize extra 65.27–261.10 million tons of standard coal (EC (European Commission), 2006b). This contravenes the energy conservation and emission policy. CCS is described as a period constrained emission reduction option. CCS are primarily designed for fossil fuel emission reduction only but other alternative energy generation mediums are developed to reduce emissions and aid in the depletion of fossil fuel reserves. This according to the research community makes alternative energy generation more attractive in terms of energy generation compared to CCS (European Commission, n.d.).

The high cost of carbon capture technology poses a challenge towards the advancement of the technology. Fig. 10 shows the cost of electricity produced from the different types of technologies under investigation. The left region of the figure explains current technologies with zero carbon options. The mid region of Fig. 10 depicts emerging technologies and the right region shows the cost of innovative systems. The dotted line shows near term electricity prices. The prices for all near zero carbon technologies are very expensive compared to current electricity cost (European Commission, n.d.).

CCS helps in reducing the total cost for combating climate change by nearly 30% as in the absence of any carbon capture technology, more expensive approach will be needed to help in the reduction of carbon dioxide during energy generation (EUIAB (European Union Impact Analysis Board), 2007). The total cost of the CSS technology is determined by the capturing costs as it accounts for 75% of the total cost. It also increases the prices of electricity between 30 and 90% (Dooley, 2006). The main reason for the increase is because there is an energy penalty related with capture and compression of CO_2 to make it ready for transport and injection. It should be noted that the cost of electricity prices from an old plant retrofitted with CCS technology is cheaper than that of a new plant with CCS.

6.1. Gasification challenges

The capture of CO_2 from a newly built gasification plant is cheaper than that of a coal plant with post combustion capture (Web.mit.edu, 2018). Below are some challenges on gasification.

a) The operational period for an IGCC plant using a gasifier and power production facilities must function at the same time. The gasification and power production are old technologies but integrating them remains a challenge for utilities.
b) The cost of building the facilities for this technology is also a major issue. IGCC in the absence of any carbon capture technology is expensive to build compared to pulverized coal without any carbon capture and storage technology (Socolow et al., 2004). Due to the challenge in securing the mandate, market price as well as the regulatory framework, recent plants are often designed without any carbon capture and storage.
c) The cost of IGCC plants is also dependent on the altitude and coal type. The higher the altitude, the more expensive to operate

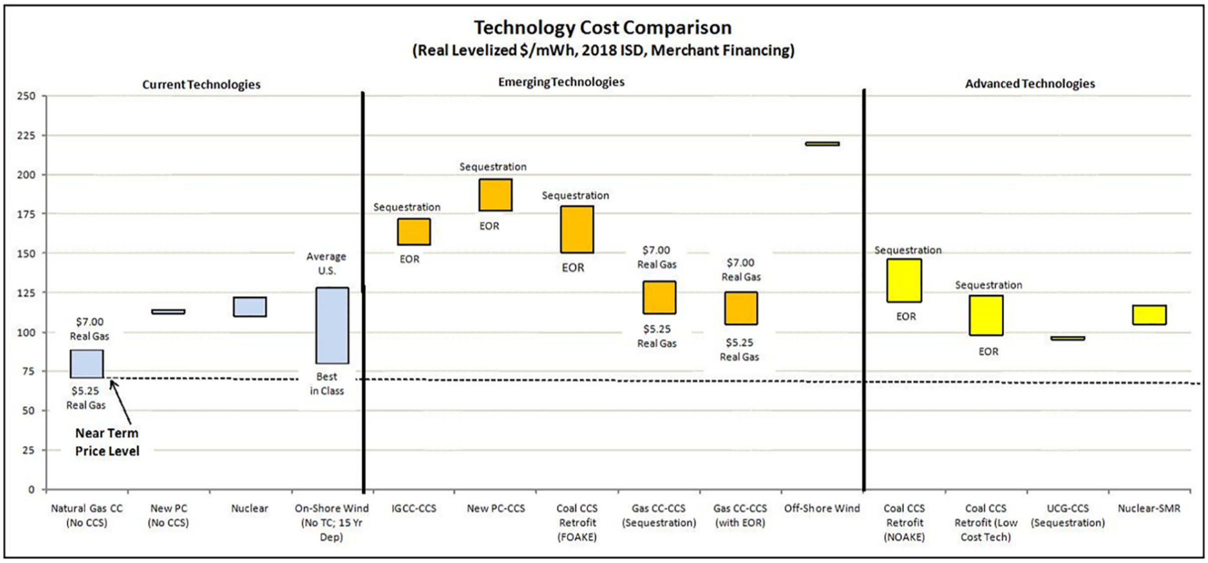
6.2. Post combustion capture challenges

The main challenges of this CCS type are the high cost and high energy penalties. The electricity produced from traditional coal power plants with post combustion capture is expensive. The levelized cost of electricity is likely to increase to 80% with this type of technology.

a) Retrofit cost for existing plants will be site specific but could approach one half the cost of building a new coal power plant without post combustion capture.
b) There is also high efficiency penalty on coal power plants. The energy needed to heat todays post combustion capture solvents and then compress carbon dioxide from the exhaust stack to pipeline pressure can reduce the output of an existing plant by 30%. These inefficiencies lead to more coal being used for an equivalent amount of electricity sold and this results in increased plants cooling requirements.
c) Incremental improvements in the efficiency and costs of PCC processes are likely following initial commercial-scale demonstrations. Technology developers to date have had little incentive to optimize solvents and process configurations (EC (European Commission), 2006b).

6.3. Geologic storage challenges

Scaling up the technology to address climate change remains a major issue with regards to sequestration. Even though the enhanced oil recovery has been used in recent times on large scale, there are still few sites where large amounts of carbon dioxide



Real levelized cost metric escalates from 2018 at 2.5% annually.

Fig. 10. Comparison for various technologies for electricity generation (Intergovernmental Panel on Climate Change, 2005).

have been injected into geologic brine formations (MIT, 2007; Fossiltransition.org, 2018). Larger field demonstration projects are needed worldwide. Science and industry experience strongly indicate that sequestration is safe when practiced in an appropriate site. However, managing hundreds of sources injecting into a single sedimentary basin requires a high level of knowledge sharing and project coordination, as well as research and development support. Monitoring, permitting and long-term care programs must also be developed so that commercial and public sequestration sites can be developed and environmental protection assured. A robust public policy framework must support the development of these institutions (Fossiltransition.org, 2018; Zhang et al., 2018a; Zhang et al., 2018b; International Energy Agency, 2013).

7. Conclusion

This paper reviewed the main technologies for carbon capture and storage (CCS) and indicated future prospects of them. Various separation techniques of CO2 including physical, membrane and Cryogenic were presented. The three main methods used in CCS including pre combustion, post combustion and oxy combustion were discussed. It was found that the post combustion and the pre combustion are the most accepted methods for CCS technology commercially. These two methods are also preferred for gas stream purification for various industrial purposes. They can also be used to absorb carbon dioxide from flue gases of small scale power plant installations but this has not been commercialized. The oxy combustion method of carbon dioxide capture is still going through developmental stages but gradually making predominant strides in the CCS industry. The merit and demerit of all CCS technologies were presented. The high cost of CCS technology is the major challenge that cut across all the three types of the technology. Carbon dioxide capture requires large energy and this is one of the reasons for the high cost of technology. For example, almost 15–30% energy is required per net kWh for new power plants powered by fossil commodities. This is the case for most combustion power plants where there is high energy penalty during the carbon dioxide capture and this increases the overall cost of the system. It is worth to mention that renovating carbon dioxide system for existing power plants is more expensive compared to new plants in terms of kWh. Therefore, CCS technology still requires significant developments to reduce the total cost of the technology in order to reach the market at affordable prices.

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